Photon-Jet studies at RHIC

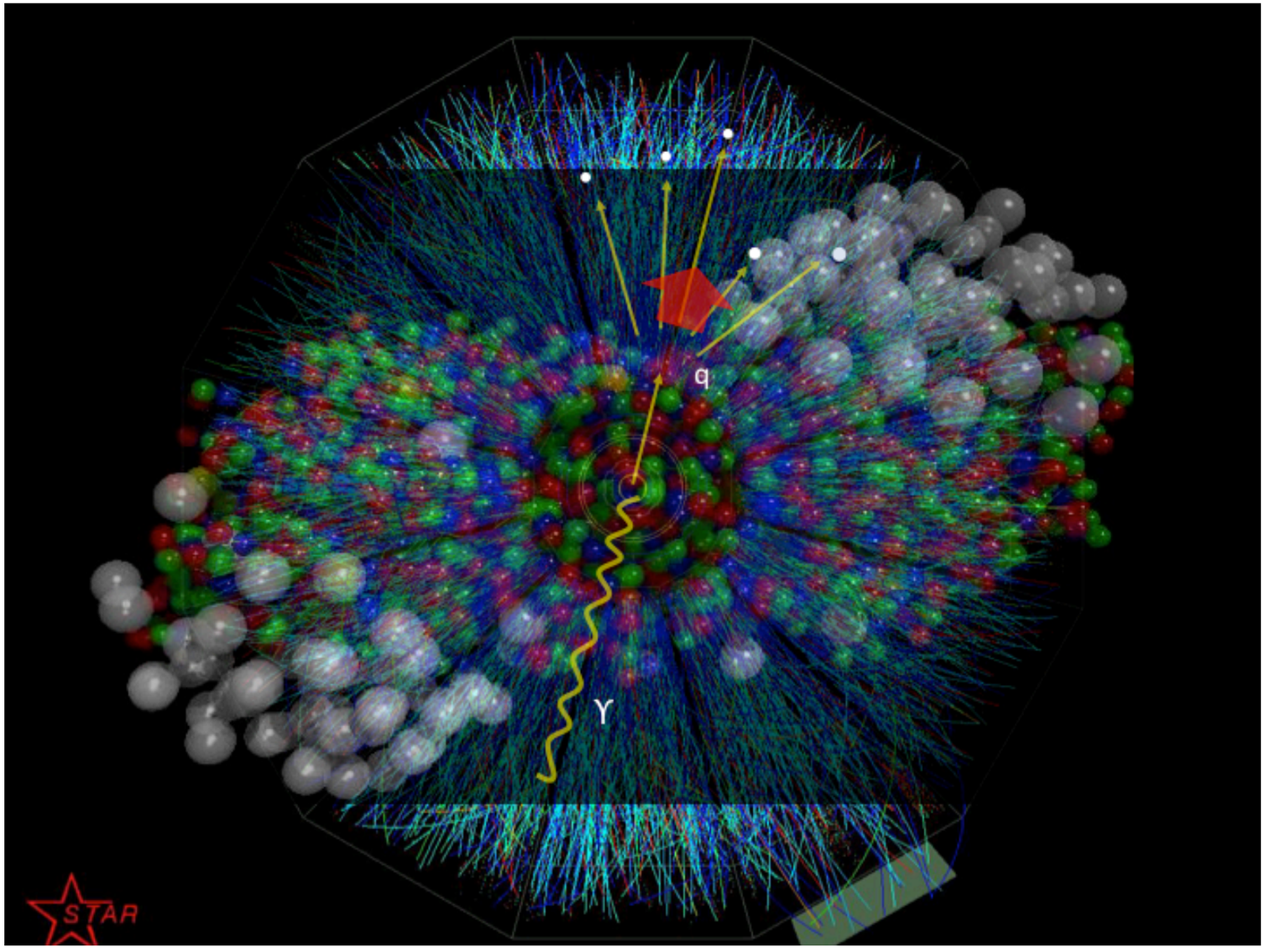
Recent jet-like correlation measurements
and a way towards photon-triggered jets at RHIC

Nihar Ranjan Sahoo

Texas A&M University

RHIC/AGS Annual Users' Meeting, 2016

Why we should study γ-jet in heavy ion collisions ?



Direct photon+jet coincidence is a good tomographic probe to study the QGP in HIC

- Doesn't interact with QCD medium
- Transverse energy approximates that of initial parton pT in γ-jet events
- volume emission dominates for γ-trigger events

Compelling measurements:

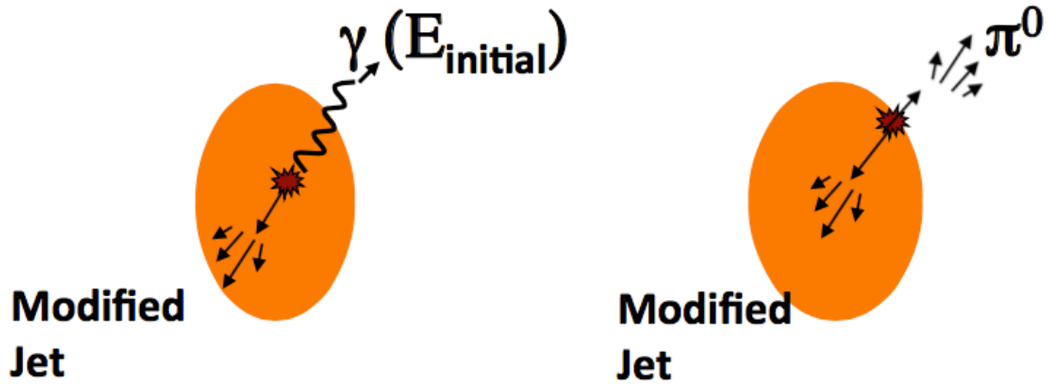
- γ-hadron correlations (advantage in AuAu due to bg.)
- γ-tagged jet reconstruction

What physics we are looking for ?

- Parton energy loss in QCD medium depends on
  - Initial energy of parton, color factor, path length, gluon density, transport coefficient, etc.

An interesting comparison with π^0-jet

- Recoil parton from direct photon predominantly quarks, whereas that of π^0 are gluons (D. de Florian et al., PRD 91, 014035 (2015),T. Kaufmann et al., PRD 92, 054015 (2015))
  - γ-triggered parton (jet) loses less energy than that of π^0-trigger
    - due to color factor ($C_A/C_F = 9/4$)
- γ-triggers are mainly volume emission, whereas π^0-triggers are surfaced biased
  - on ave. γ-triggered parton (jet) loses less energy than that of π^0-trigger
    - due to path length
- Energy loss as a function of
  - Trigger p_T of direct photon
  - Associated hadron p_T



Experimental techniques and challenges

- Direct photon discrimination from neutral hadrons (like π^0,η)
  - STAR experiment: Transverse shower profile method
  - PHENIX experiment: Statistical subtraction method (from meson decays)
  - Isolation cuts
- Background subtraction
  - Underlying event bg., flow component in azimuthal correlations, etc…
    both in γ-hadron correlation and in γ-tagged jet reconstruction
- Different systematic effects from unknown sources
- Finally, we need large statistics

Observables at RHIC

$$I_{AA}(x) = \frac{Y^{Au+Au}(x)}{Y^{p+p}(x)}$$

Ratio of Au+Au to p+p per trigger yields

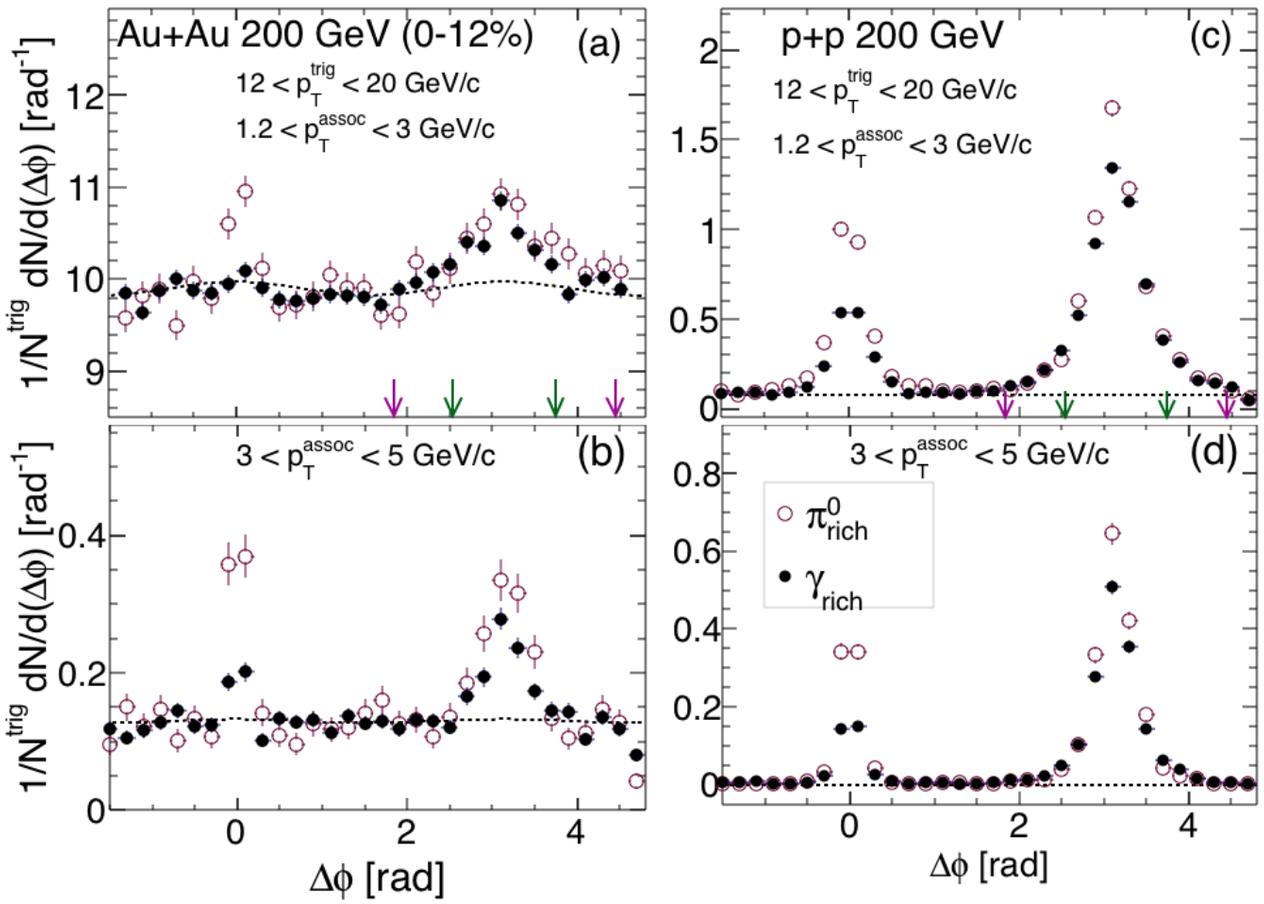
Where $x = p_T^{\gamma}$ — Trigger p_T

$= p_T^{assoc}$ — Associated hadron p_T

$= z_T \quad (= \frac{p_T^{assoc}}{p_T^{\gamma}})$ — Fraction of momentum carried by the away-side hadron

Jet-like azimuthal correlation functions

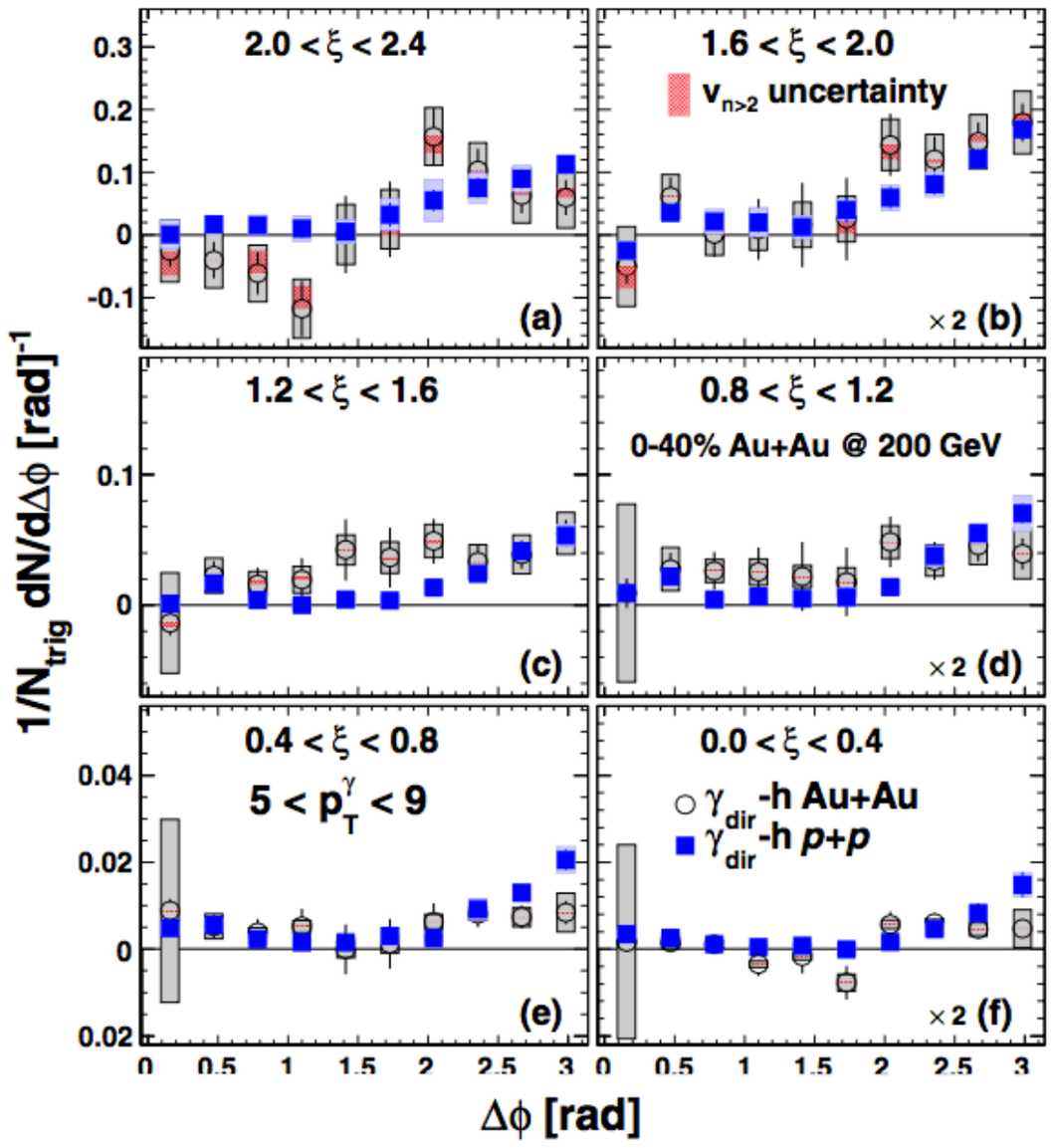
STAR experiment



arXiv:1604.01117

- In γ_{rich} small peak due to some contamination of π^0
- Background subtracted from flow modulated background level determined using ZYA1 method
- Near-side yield is by definition zero for direct-photon trigger

PHENIX experiment



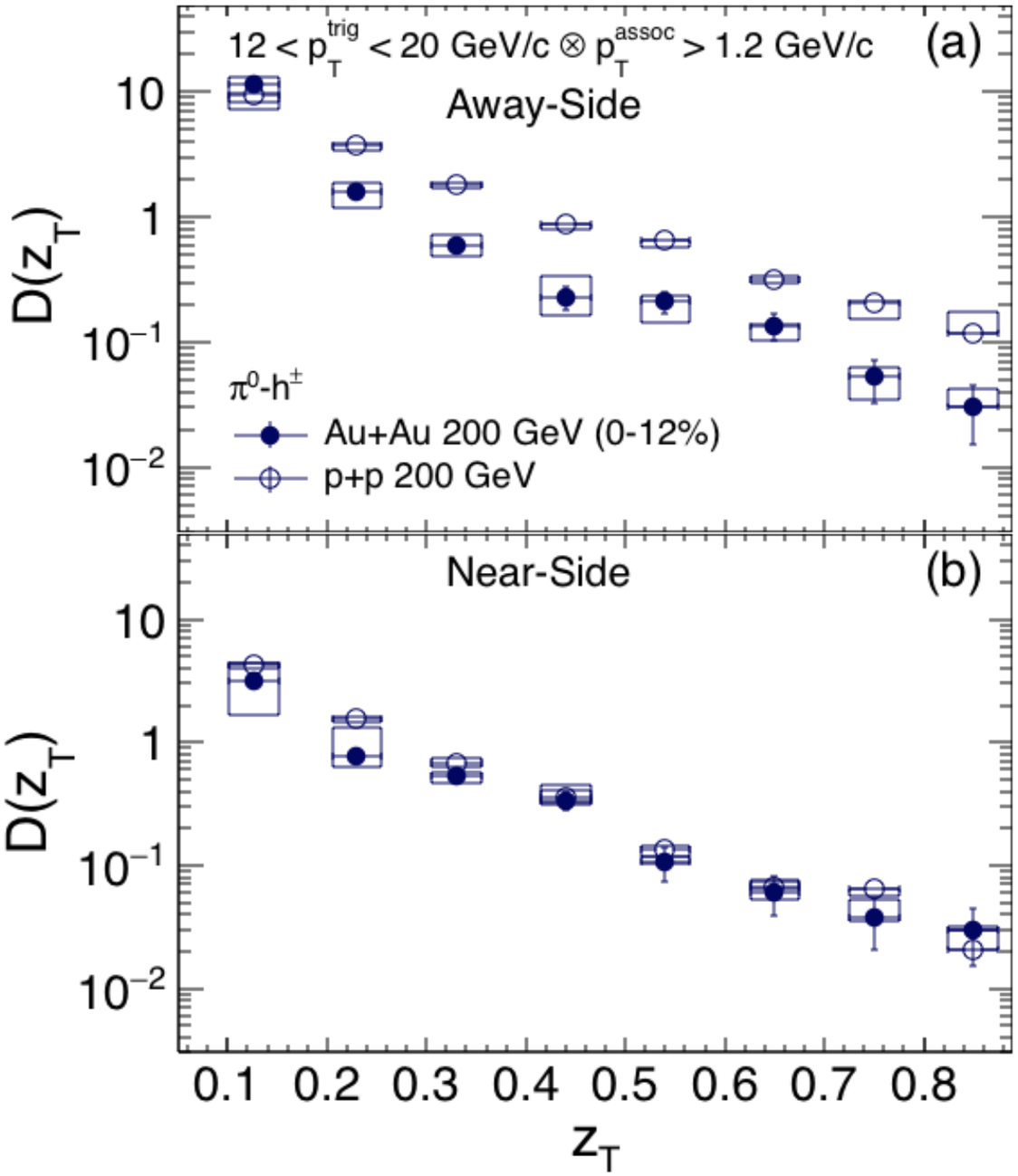
$\xi = \ln(1/z_T)$ PRL 111, 032301 (2013)

- γ_{dir}-hadron correlations in **p+p** and **Au+Au**
- At low z_T, sys. uncertainty due to higher flow (n>2) components seems noticeable in Au+Au

Associated yields of π^0-hadron correlations

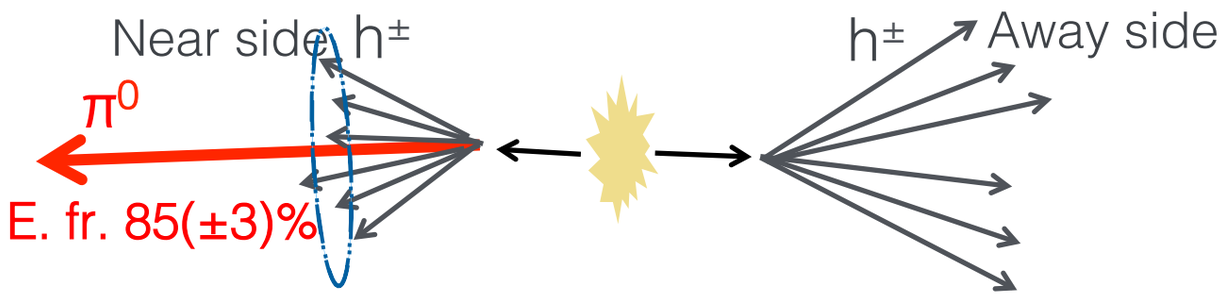
From STAR experiment

Some discussion of π^0 –hadron correlations

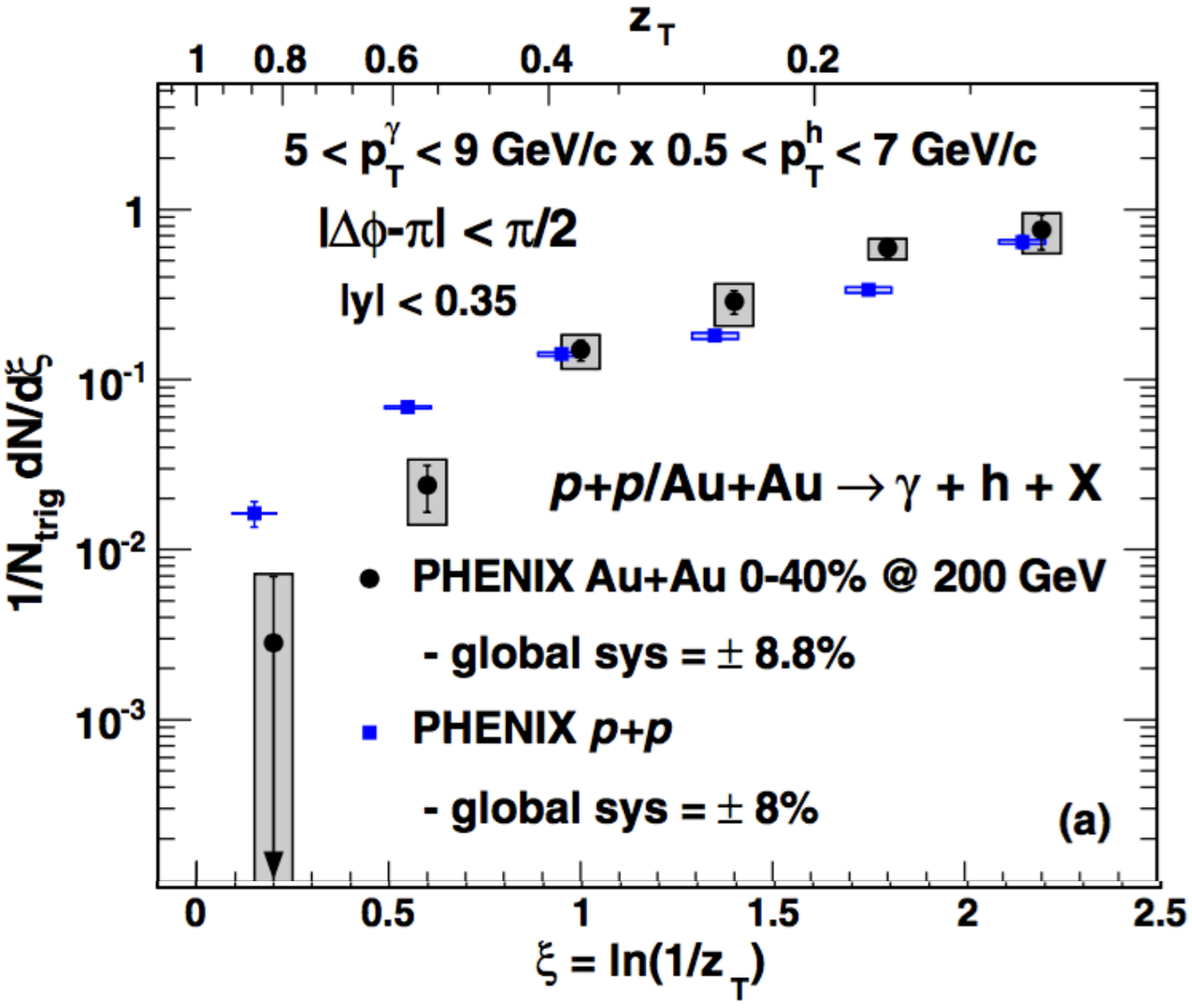


arXiv:1604.01117

- Near-side and away-side yields are extracted within $|\Delta\phi| \leq 1.4$ and $|\Delta\phi - \pi| \leq 1.4$
- Away-side yields show suppression
- Near-side shows no suppression
- By integrating z_T times near-side yields, STAR exp. estimated 85(±3)% fraction of energy carried by π^0 over "jet energy" (π^0 + charged hadrons) in pp 200 GeV
- In PYTHIA, it is found to be 80(±5)% which is consistent with data



Yields associated with Υ_{dir} – trigger: Fragmentation function



PRL 111, 032301 (2013)

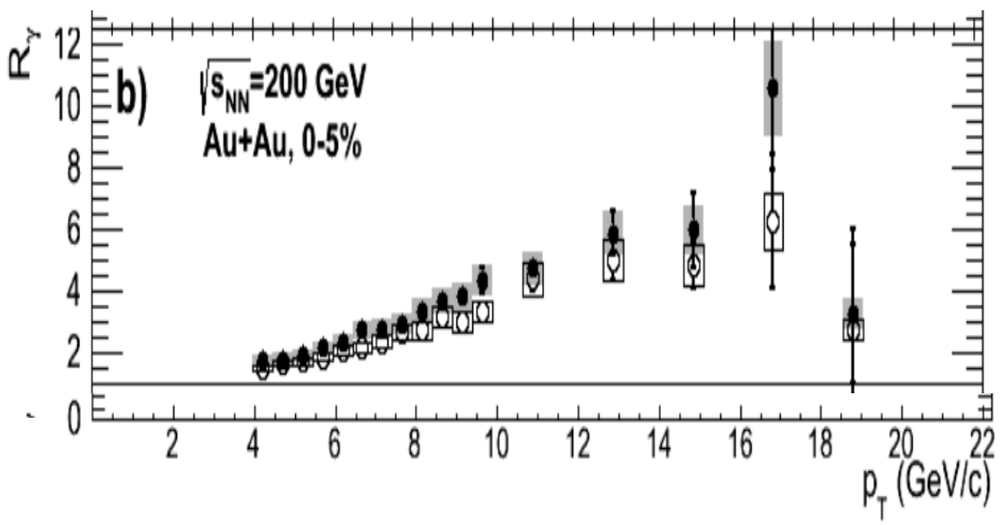
PHENIX experiment

Using statistical subtraction method:

$$Y_{\mathrm{dir}} = \frac{R_\gamma Y_{\mathrm{inc}} - Y_{\mathrm{dec}}}{R_\gamma - 1}$$

Where, $Y_{inc} = \frac{1}{N_{inc}} \frac{dN^{h-\gamma_{inc}}}{d\Delta\phi}$

$R_\gamma = \frac{N_{inc}}{N_{dec}}$ ~1.4 to ~2.3 vs. p_T

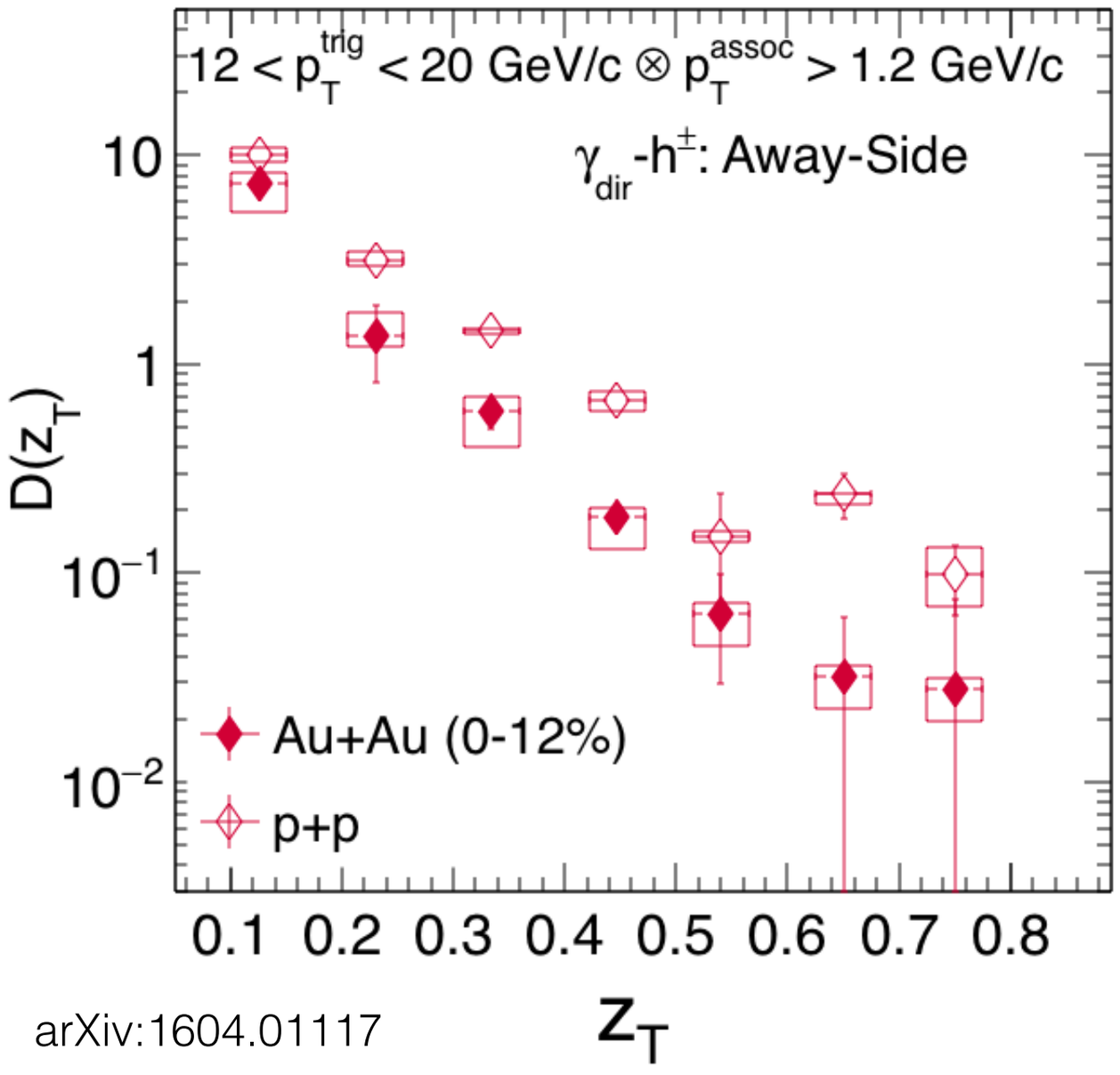


PRL 109, 152302 (2012).

- Fragmentation function is modified
- Not const. at all z_T/ξ

Yields associated with Υ_{dir} – trigger: Fragmentation function

STAR experiment



arXiv:1604.01117

$$Y_{\gamma_{dir}+h} = \frac{Y^{a}_{\gamma_{rich}+h} - RY^{a}_{\pi^0+h}}{1-R}$$

$Y^{a(n)}_{\gamma_{rich}+h}$ and $Y^{a(n)}_{\pi^0+h}$: away-side (near-side) yields of associated particles per γ_{rich} and π^0 trigger, respectively.

Purity of γ^{rich} sample

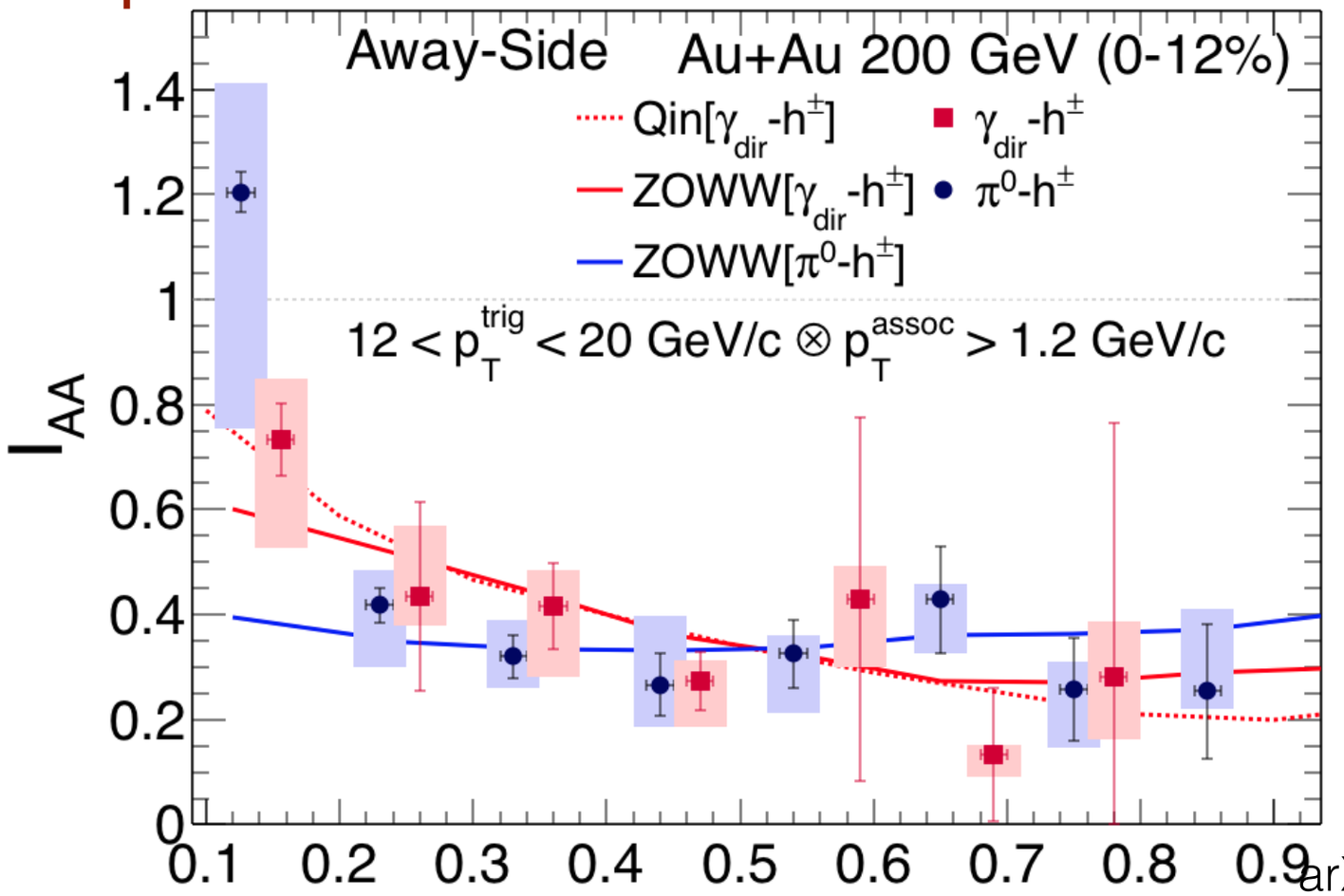
$$1-R = \frac{N_{\gamma^{dir}}}{N_{\gamma^{rich}}}$$

(1-*R*) are ~40% and ~70% for p+p and Au+Au central (0-12%) collisions, respectively

- Fragmentation function is modified
- Away-side yields show suppression in Au+Au collisions as compared with p+p

Nuclear modification factor: I_{AA} of Υ_{dir} and π^0

STAR experiment



arXiv:1604.01117

Qin:
G.-Y Qin et al.,PRC 80, 054909 (2009)

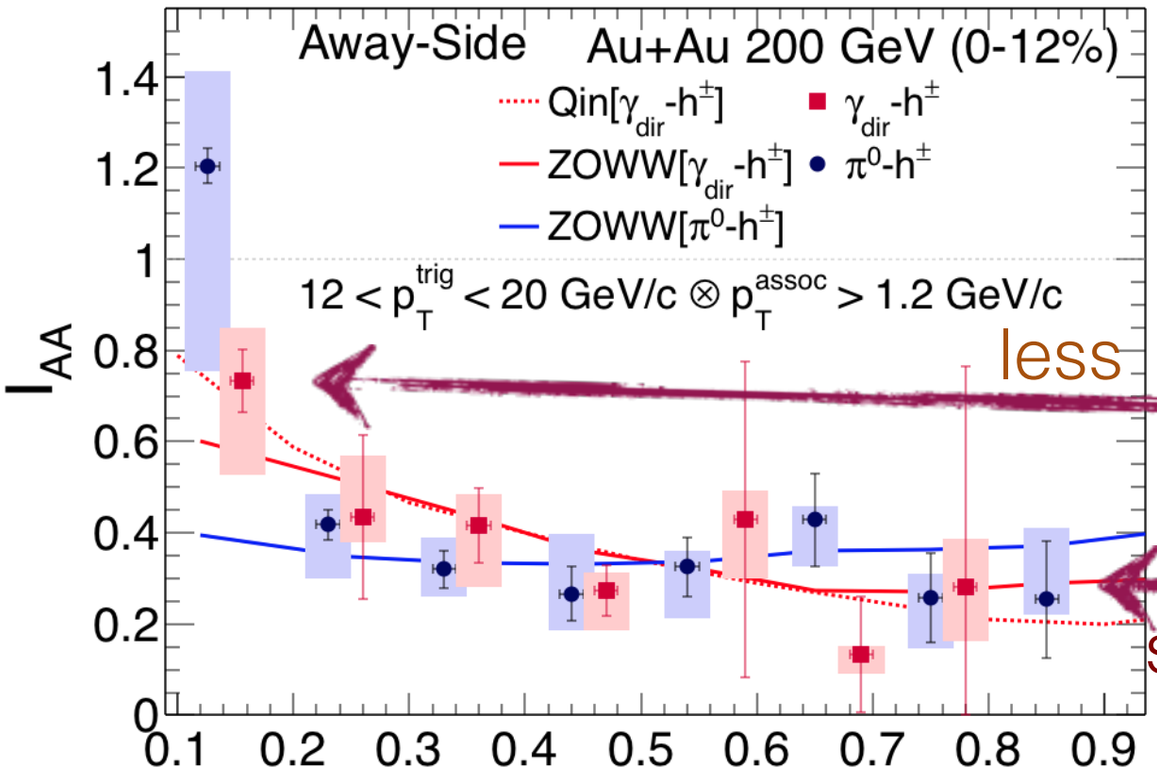
ZOWW:
X. N. Wang et al.,
Phys. Rev. C 84, 034902 (2011)
Phys. Rev. C 81, 064908 (2010)
Phys. Rev. Lett. 103, 032302 (2009)

- *Within large uncertainties,* $I_{AA}^{\pi 0\text{-h}}$ and $I_{AA}^{\Upsilon dir\text{-}h}$ show
  - similar suppression : No clear path length and color factor effect observed
  - strong suppression: particularly for $z_T > 0.2$
- Indication of less suppression at low zT, but not significant
  - More significant effect in I_{AA} (p_T^{assoc})
- Models are consistent with data

Nuclear modification factor: I_{AA} of Υ_{dir}

STAR experiment

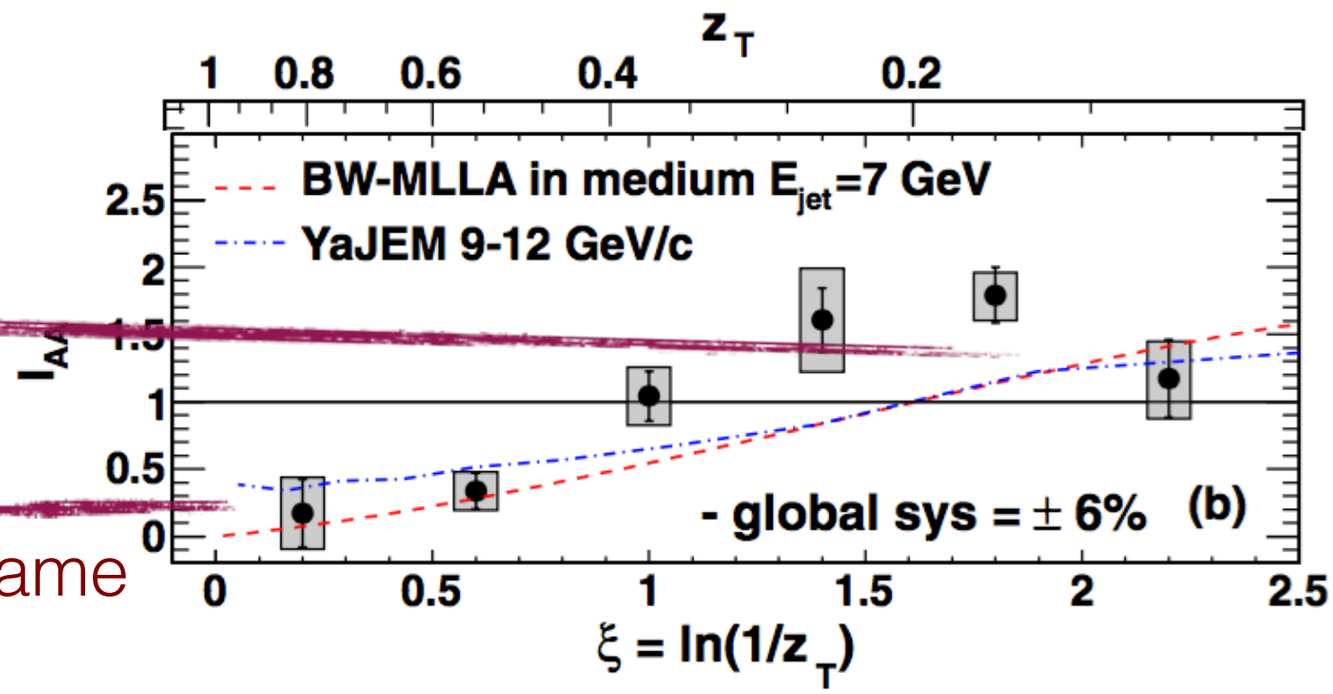
$12 < p_T^{trig} < 20$ GeV/c



arXiv:1604.01117

PHENIX experiment

$5 < p_T^{trig} < 9$ GeV/c



PRL 111, 032301 (2013)

less

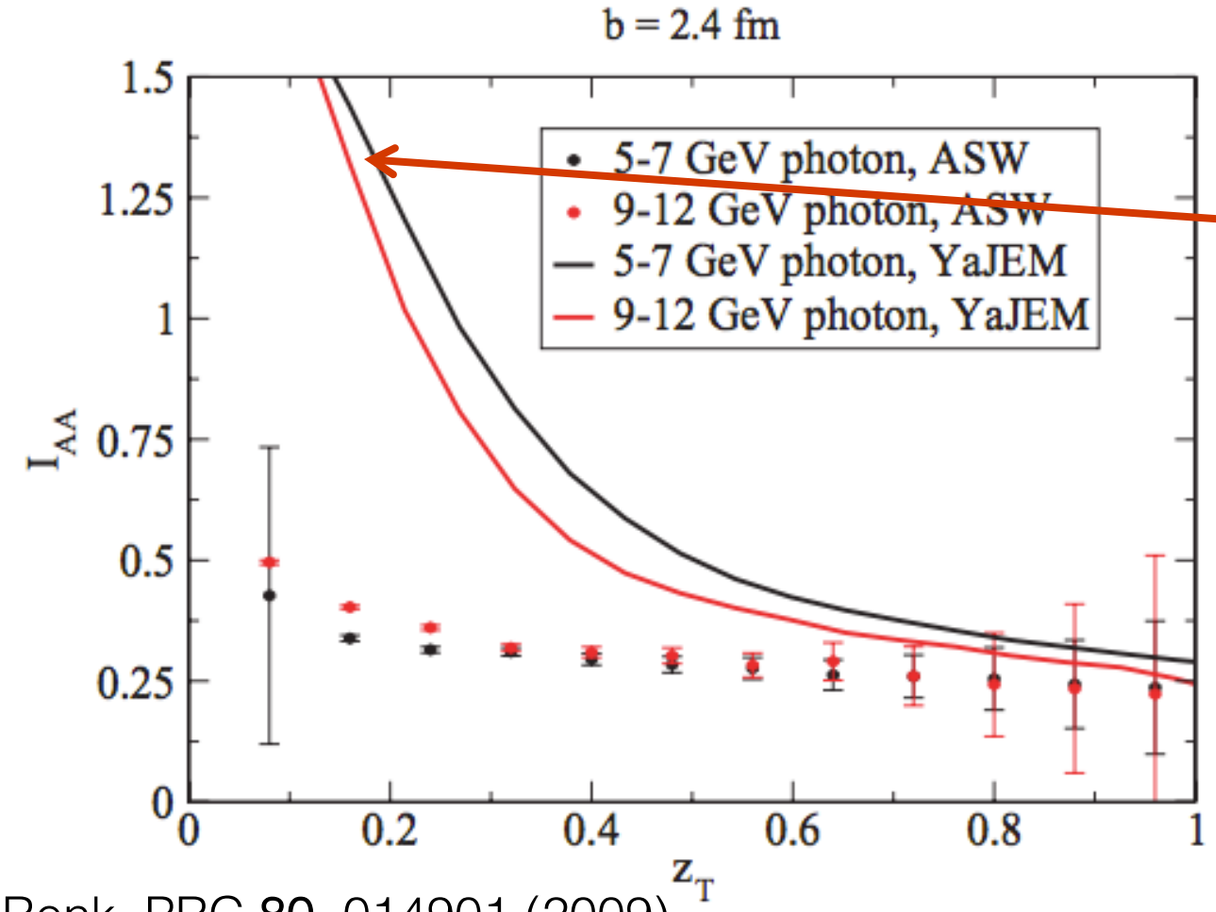
same

- At low z_T, I_{AA} is less suppressed at high p_T^{trig} than at low p_T^{trig}
- At high z_T, similar level suppression in both p_T^{trig} regions

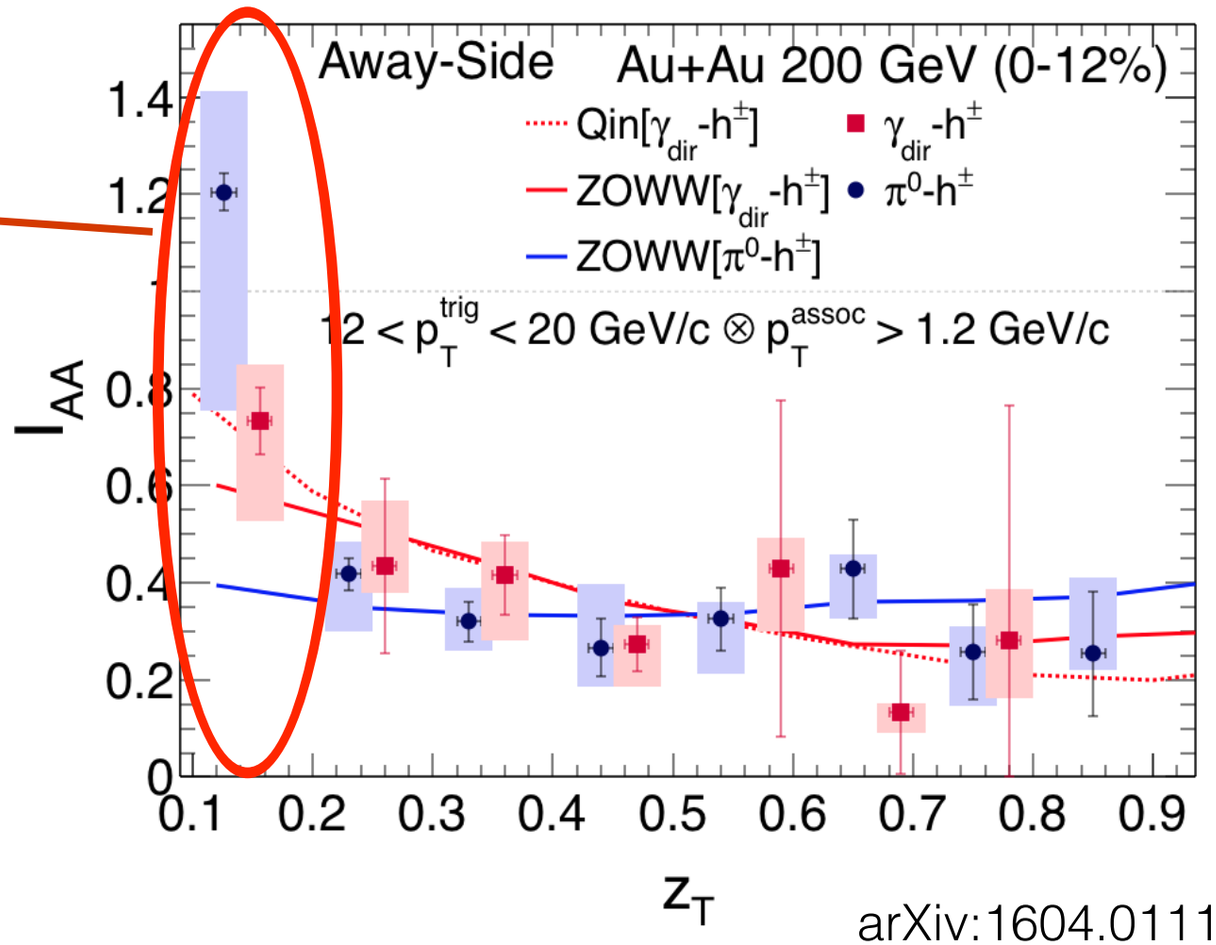
- Redistribution of energy in YaJEM model to differentiate between PHENIX and STAR I_{AA}
- Qin, ZOWW models don't show enhancement at low z_T (for 12-20 GeV/c)

Comparison with other theoretical model

Only considering trend of I_{AA} as a function of z_T



T. Renk, PRC **80**, 014901 (2009)



arXiv:1604.01117

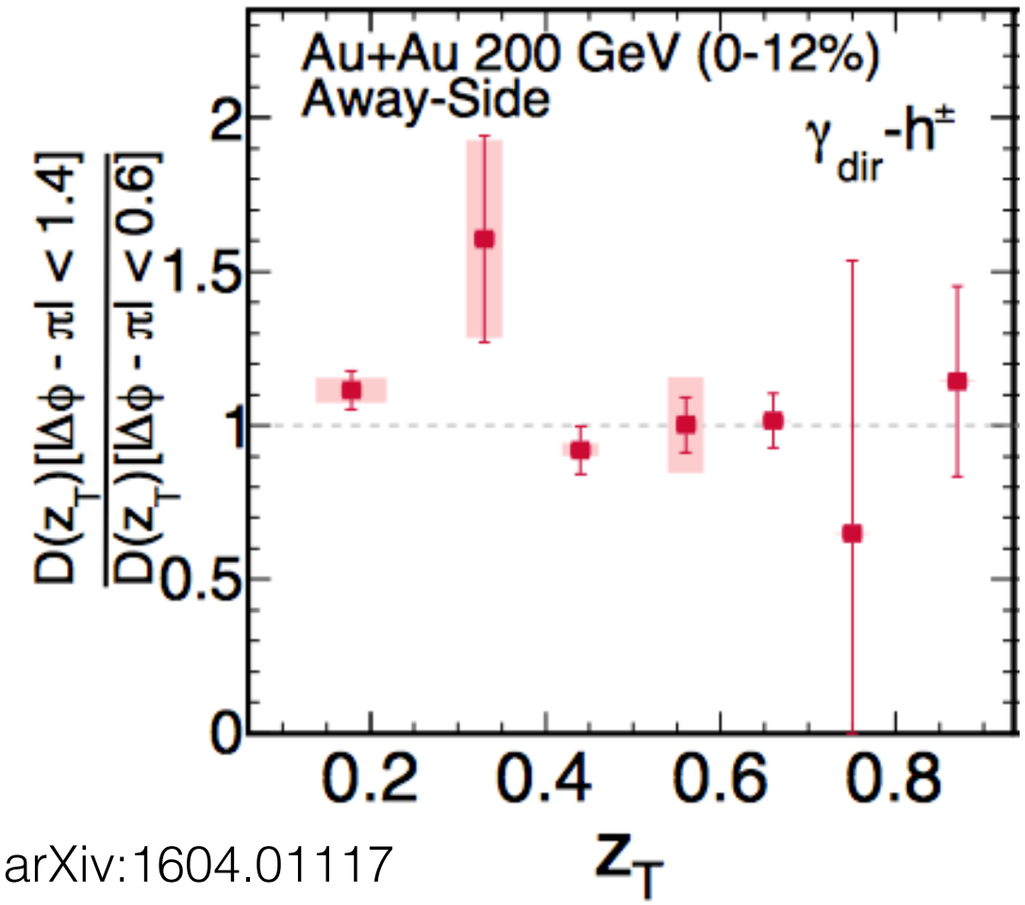
Unlike Qin, ZOWW models, YaJEM model includes energy loss by gluon radiation that redistributed to soft particles

Hence, large enhancement at low z_T compared with high z_T

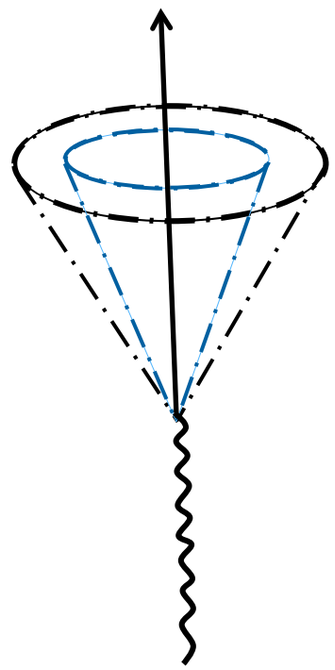
Energy loss in azimuthal windows

STAR experiment

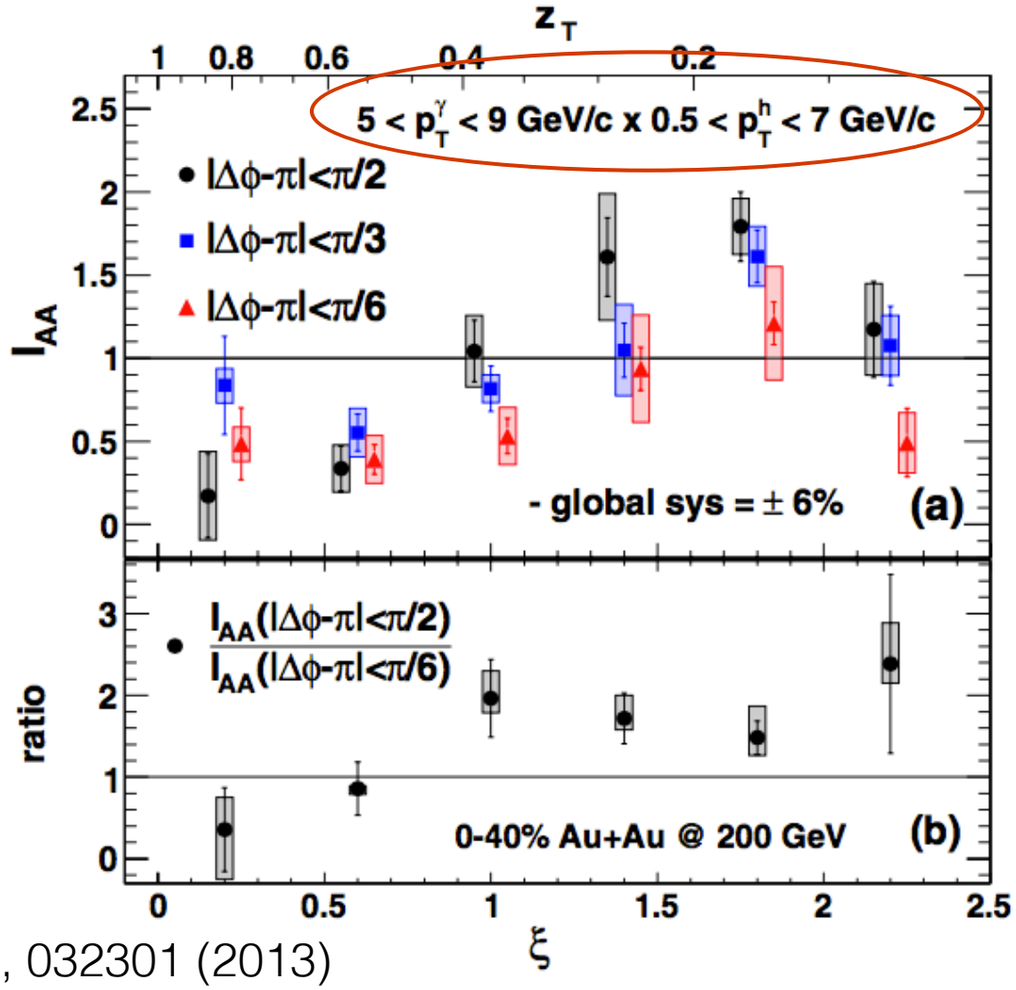
$12 < p_T^{trig} < 20$ GeV/c [$\pm 35^0$ vs $\pm 80^0$]



arXiv:1604.01117



PHENIX experiment



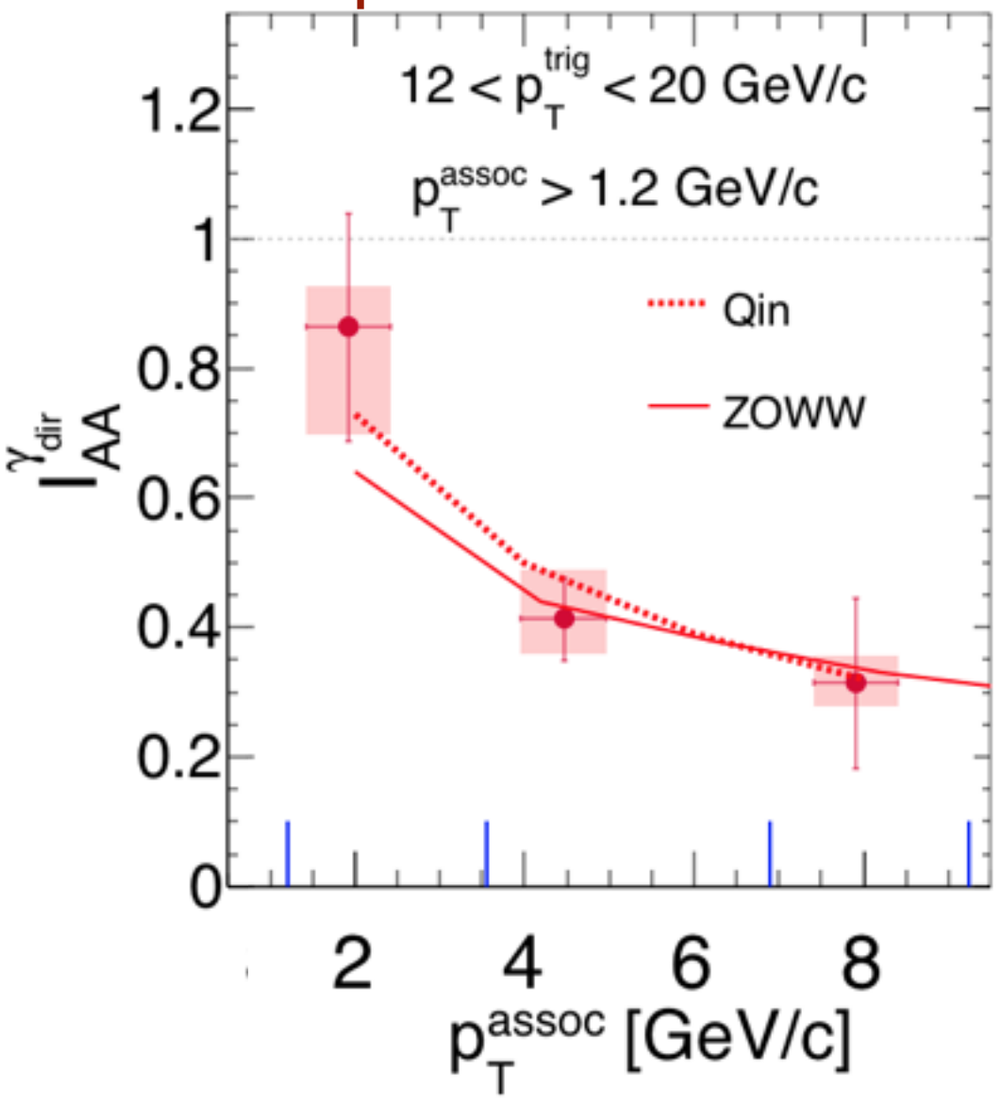
PRL 111, 032301 (2013)

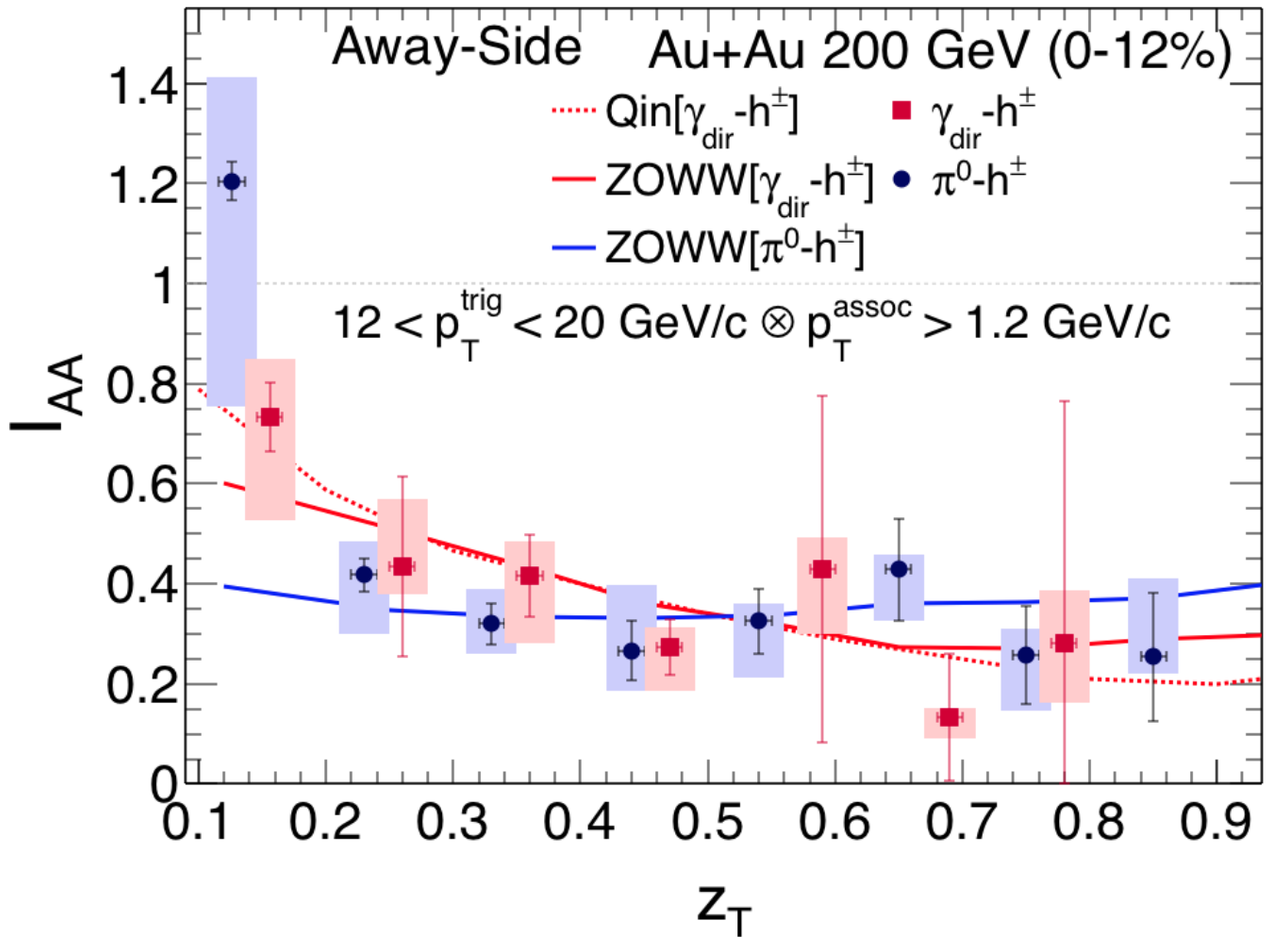
- High trigger p_T, no recovery of energy loss even at wider azimuthal angle
  [$12 < p_T^{trig} < 20$ GeV/c ➔ $0.1 < z_T < 0.4$ ➔ $1.2 < p_T^{asso} < 8$ GeV/c]
- Low trigger p_T, recovery at smaller z_T
  [$5 < p_T^{trig} < 9$ GeV/c ➔ $0.1 < z_T < 0.4$ ➔ $0.5 < p_T^{asso} < 3.6$ GeV/c]

soft particles coming out at wider azimuthal window !!!!

Energy Loss as a function of associated hadron p_T

STAR experiment



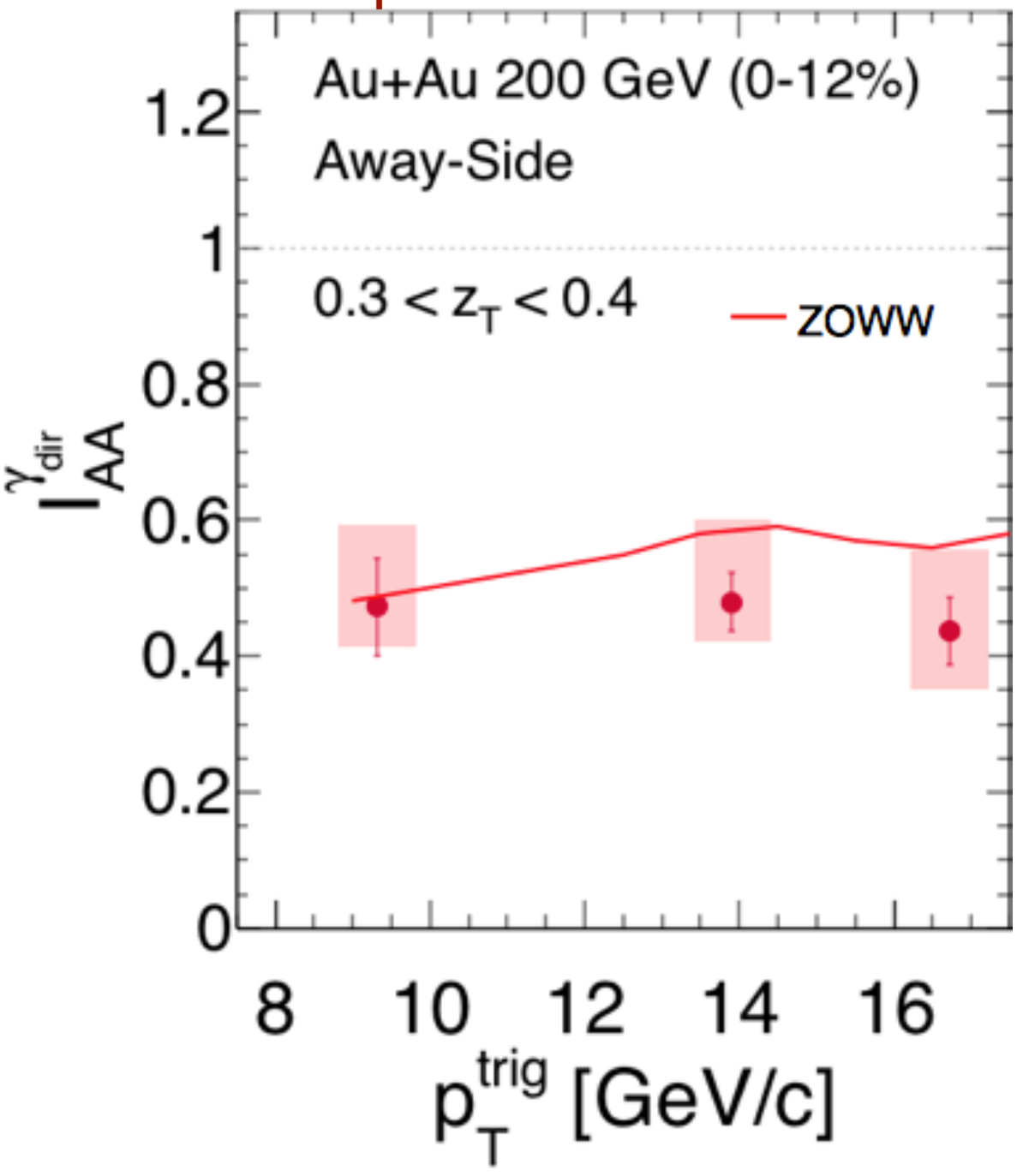


arXiv:1604.01117

- Soft associated particles are less suppressed compared with high p_T
- Energy loss as a function of z_T and associated hadron p_T respond similarly

Energy Loss as a function of triggered direct photon p_T

STAR experiment



Energy loss is insensitive to the energy of triggered direct photon at high p_T (8-20 GeV/c)

arXiv:1604.01117

What we have observed so far ?

From RHIC measurements

- Within uncertainties, no clear path length and color factor effect observed in π^0 vs. γ triggers !!!!
  - May be these effects are very sensitive!!!!
  - **Precision measurement may be required**
- "Modified" FF not independent of p_T^{trig}
- Less suppression or even enhancement at low p_T^{assoc}
- Soft particles (p_T^{assoc} < 2 GeV/c) coming out at wider azimuthal angles
- Energy loss is insensitive to the energy of triggered γ at high p_T (8-20 GeV/c) at RHIC

What next ?

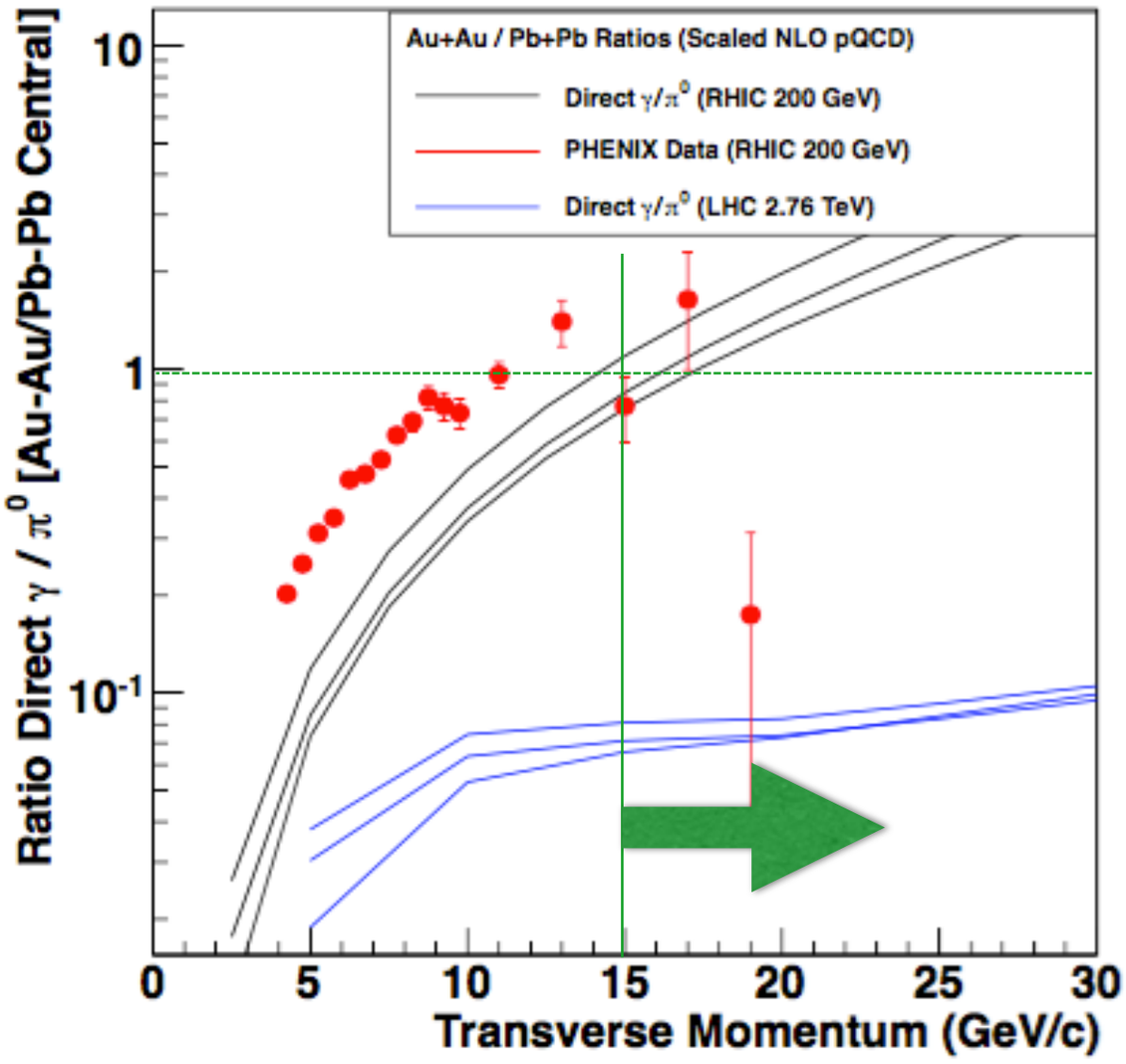
γ tagged Jet reconstruction-

Full jet reconstruction can give us full energy of away-side recoil parton

(But there are many experimental challenges)

Direct photon tagged jet reconstruction at RHIC

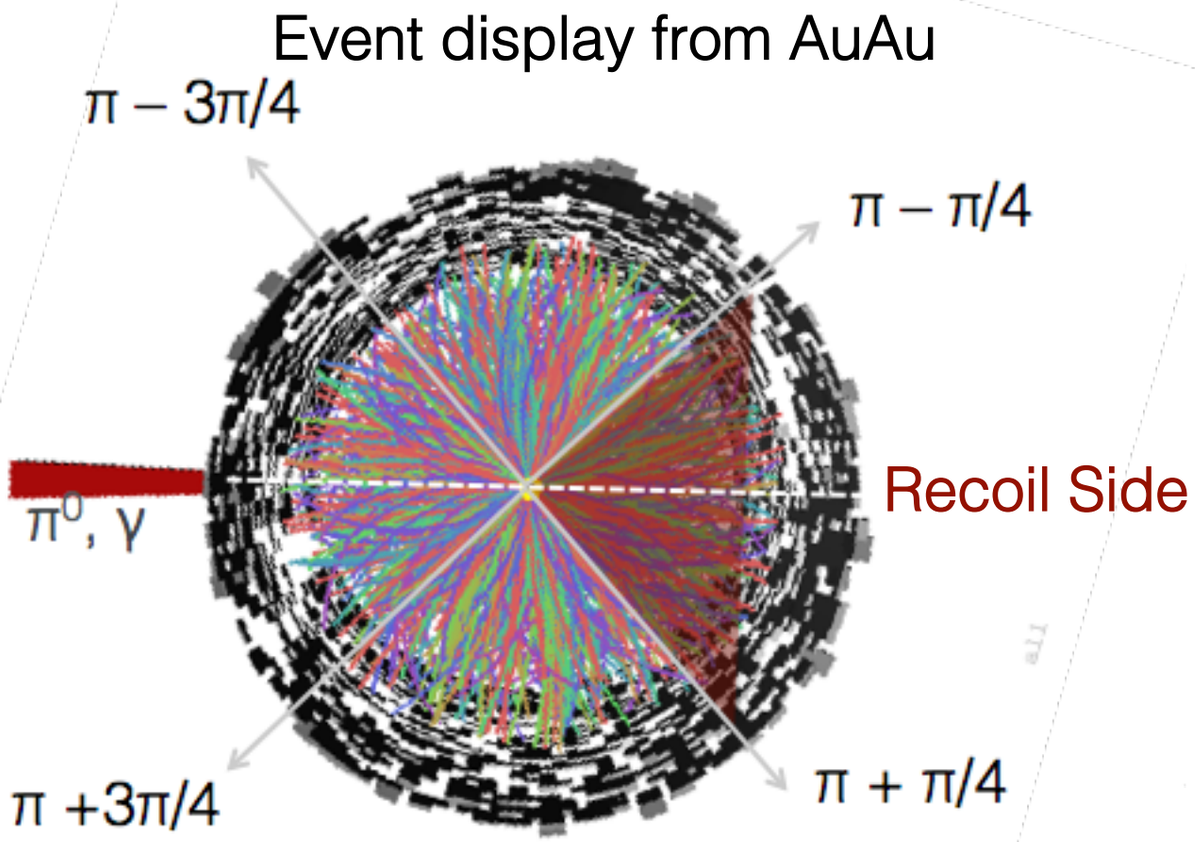
PHENIX proposal

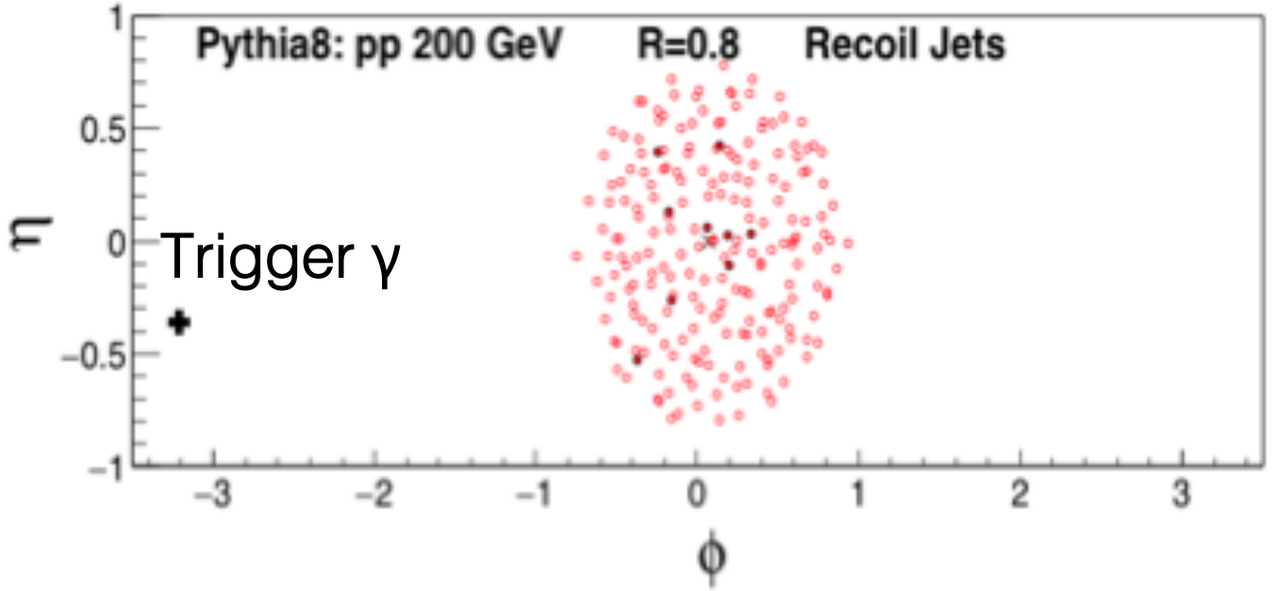


- Including π^0 suppression in HIC, γ/π^0 ratio exceeds unity above $p_T > 15$ GeV
- In pp, we need to do proper isolation cut
- It is possible to have γ-jet measurement at top RHIC
- Along with that comparison with π^0-jet measurement could also be interesting too

Better to have simulation study before data analysis…..

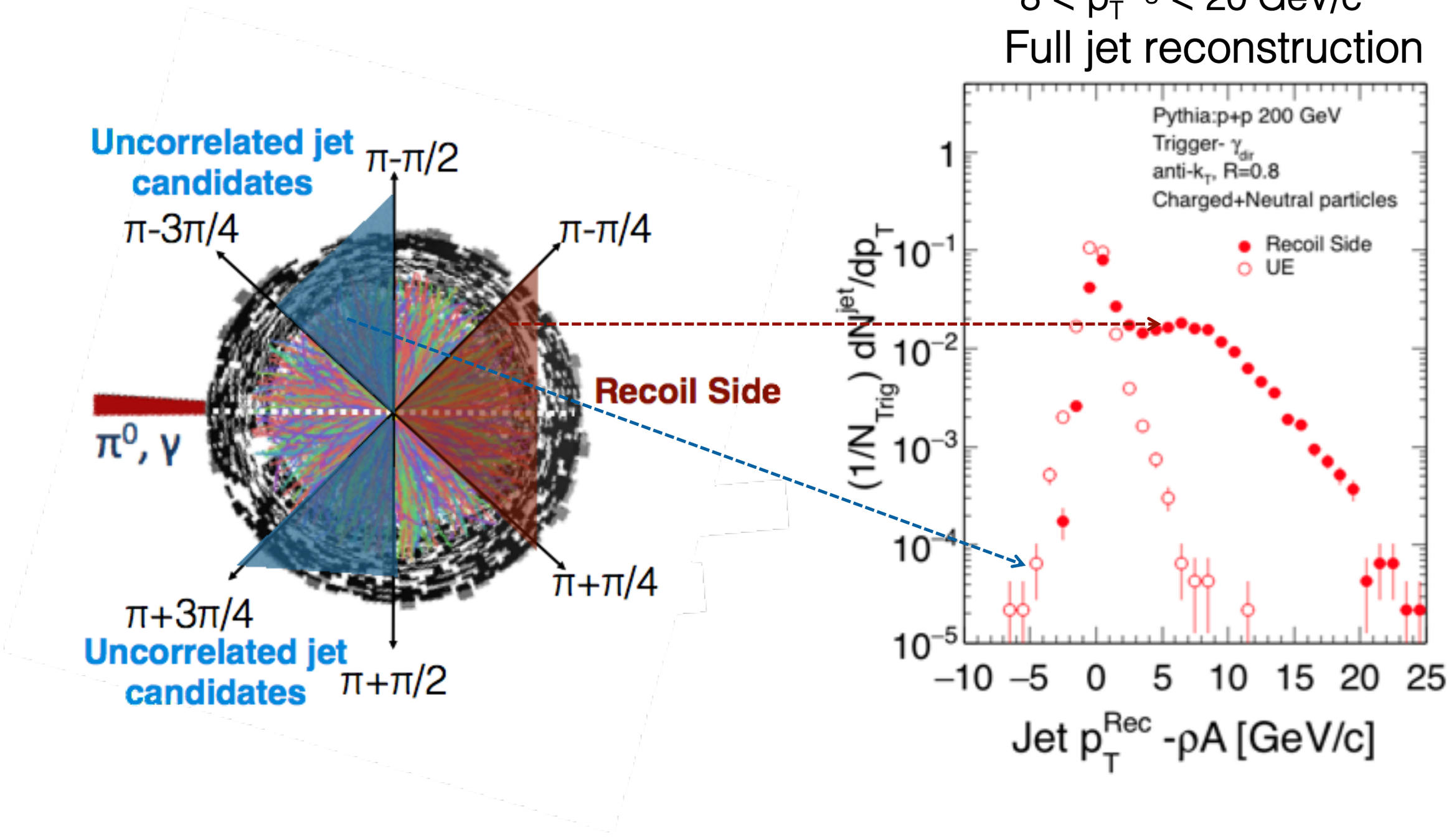
Pythia simulation study of γ-Jet measurement





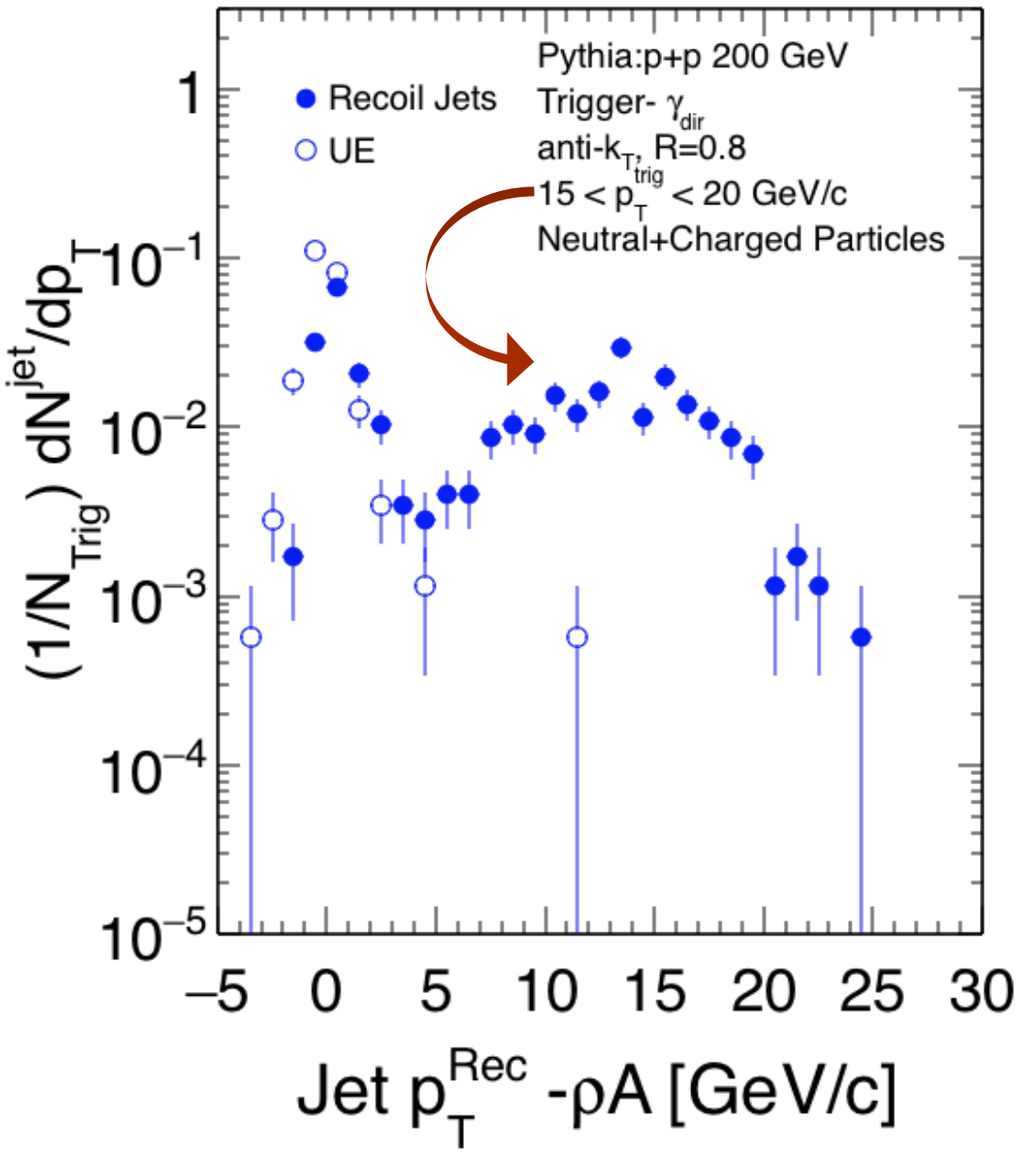
- HT trigger can provide neutral triggers (π^0,γ) in STAR experiment
- Preliminary simulation studies using Pyhthia8 have been done

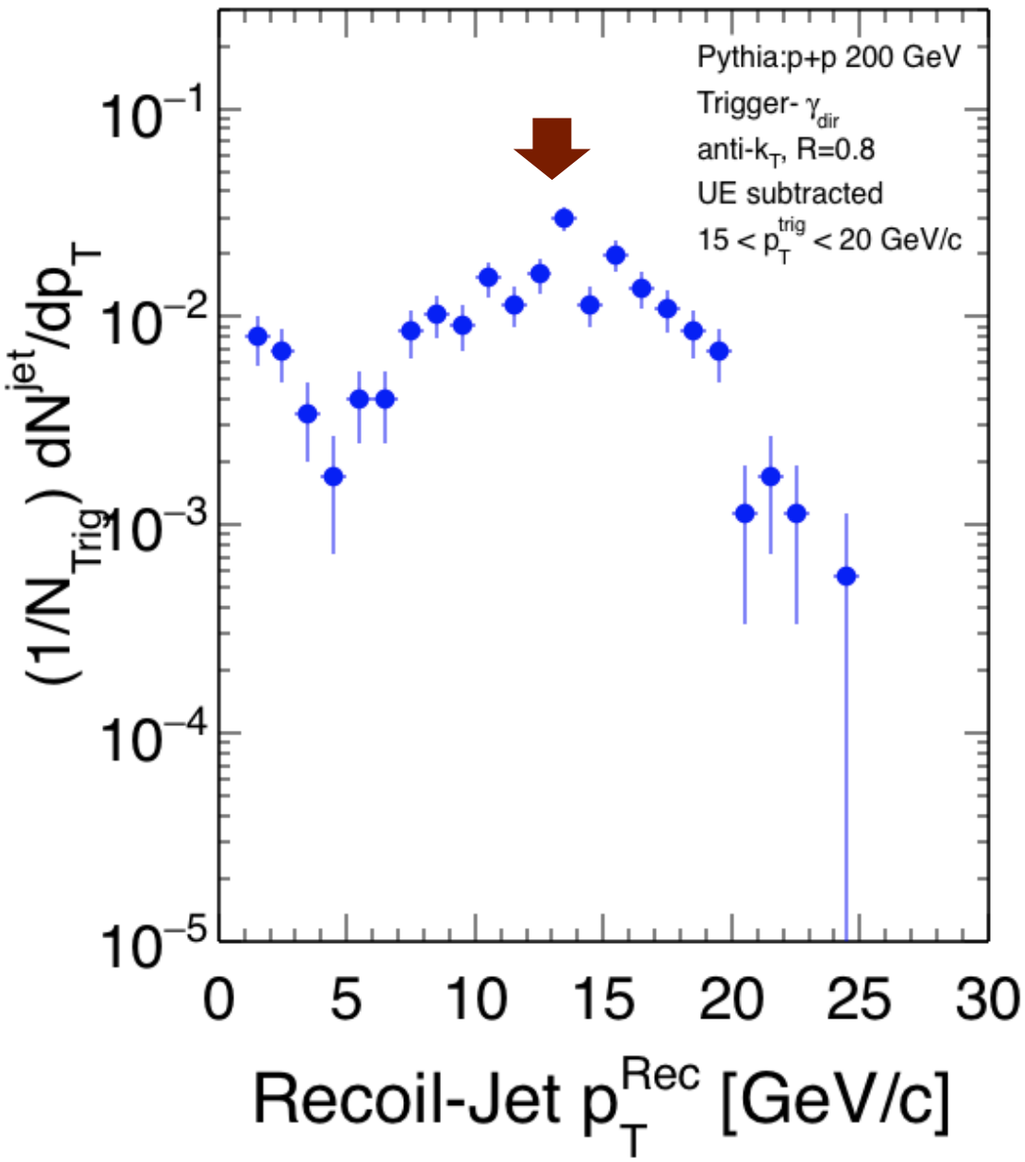
γ-tagged recoil jet in Pythia8



Uncorrelated jet are used to subtract background

Comparison charged vs full jet reconstruction





Preliminary simulation study

- For full Jet reconstruction, nice peak at $15 < p_T^{trig} < 20$ GeV/c

Work is ongoing using STAR data for Au+Au and p+p collisions…..

Summary and Outlook

- I_{AA} measurement for γ-trigger hadron correlations is discussed from low to high p_T range (5-9 and 12-20 GeV/c) at RHIC
- Within uncertainties, no clear path length and color factor effect observed in π^0 vs. γ triggers !!!!

  - May be these effects are very sensitive!!!!
  - **Precision measurement may be required**
- "Modified" FF not independent of p_T^{trig}
- Less suppression or even enhancement at low p_T^{assoc}
- Soft particles (p_T^{assoc} < 2 GeV/c) coming out at wider azimuthal angles
- Energy loss is insensitive to the energy of triggered γ at high p_T (8-20 GeV/c) at RHIC

Work is ongoing in STAR experiment to measure both γ- and π^0-tagged charged/Full jet reconstruction to have good understanding on parton energy loss at RHIC energy….

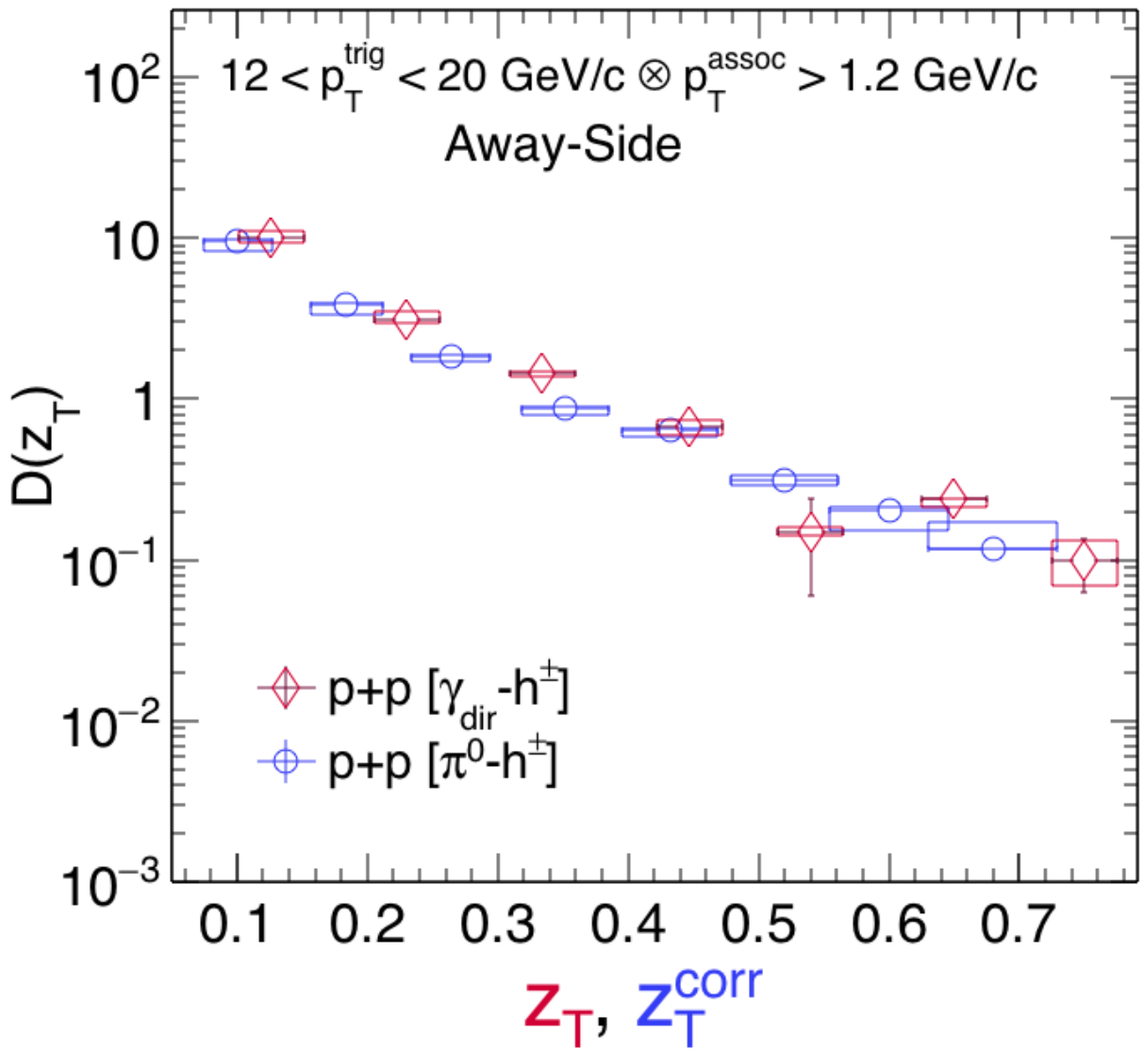
In the Future - sPHENIX …

Interesting Direct photon-Jet physics is ongoing at RHIC

Stay tuned…..

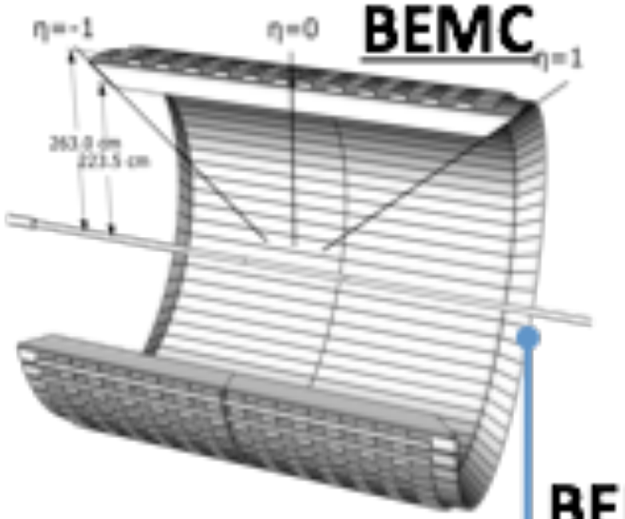
Thank you!

Back Up

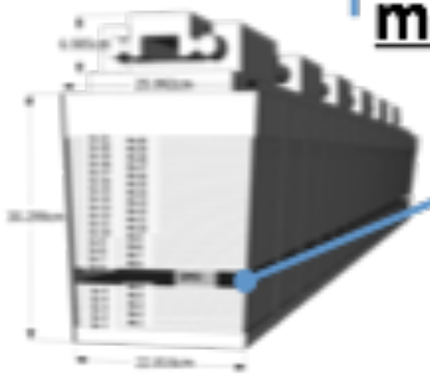

12 < p_T^trig < 20 GeV/c ⊗ p_T^assoc > 1.2 GeV/c
Away-Side
D(z_T)
p+p [γ_dir-h^±]
p+p [π^0-h^±]
z_T, z_T^corr

Transverse shower profile method

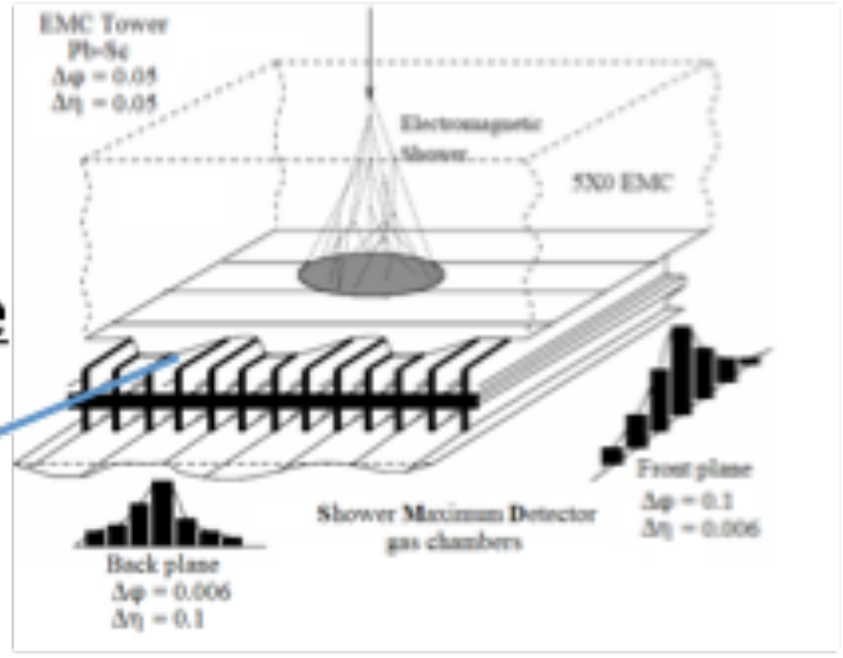
STAR BEMC



BEMC module

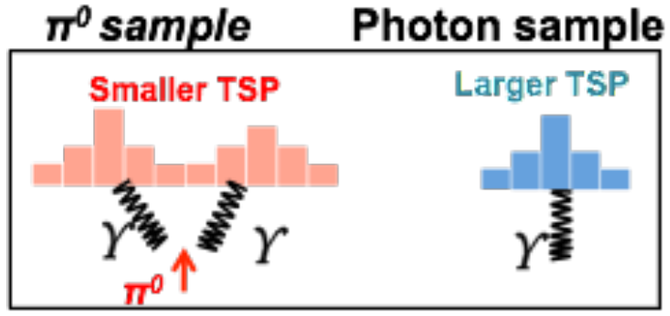


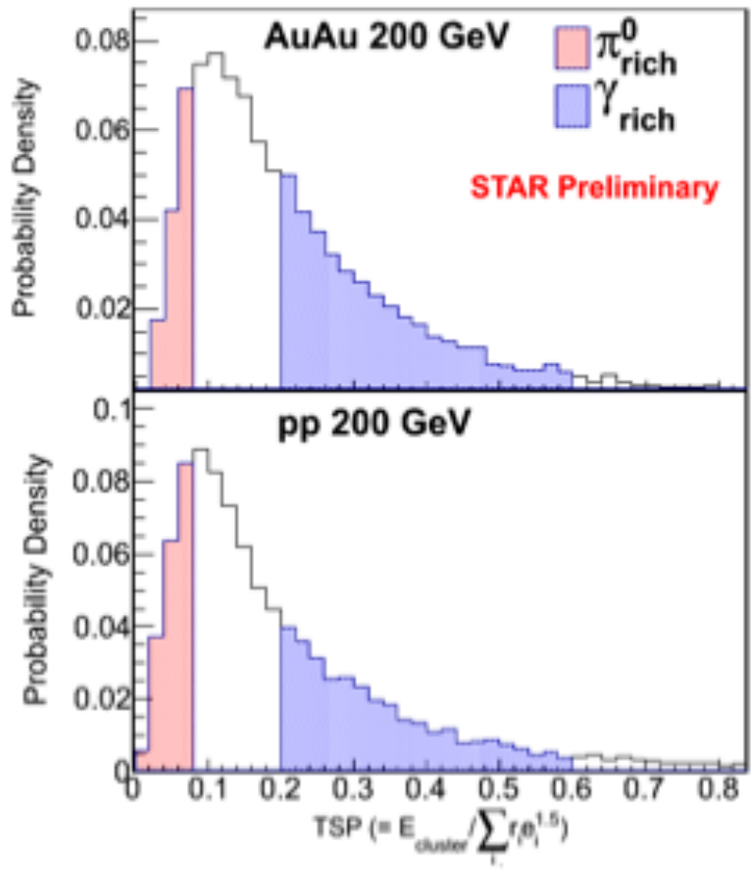
Shower Maximum Detector(BSMD)



$$\mathbf{TSP} = \frac{\mathbf{E_{cluster}}}{\sum_i \mathbf{e_i r_i^{1.5}}}$$

$E_{cluster}$: Cluster energy, e_i: BSMD strip energy,
r_i: distance of the strip from the center of the cluster





- Wider shower represents small TSP and vise versa
  - TSP cuts tuned to get
    - a nearly pure sample of π^0 (called "π^0_{rich}")
    - a sample of enhanced fraction of γ_{dir} (γ_{rich})